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Generation IV Roadmap

Technology Goals for Generation IV Nuclear Energy Systems

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TECHNOLOGY GOALS FOR GENERATION IV NUCLEAR ENERGY SYSTEMS

BACKGROUND

More than 400 nuclear power plants are currently operating throughout the world, supplying about 16% of the world's electricity. These plants perform safely and reliably and they help meet the objectives of diversity, independence, and security of their energy supply. Unlike fossil fuel plants, nuclear plants do not produce carbon dioxide, sulfur, or nitrogen oxides that are released into the environment. By 2030, the world demand for energy and electricity is projected to have risen by about 50% above today's demand, and nearly double by 2050. Growing concerns for the environment will favor energy sources that can satisfy the need for electricity and other energy-intensive products on a sustainable basis, with minimal environmental impact and competitive economics. If advances are made that fully apply the potential benefits of nuclear energy systems, the next generation of nuclear systems can provide a vital part of a long-term, diversified energy supply.

Generation IV Nuclear Energy Systems

Generation IV nuclear energy systems comprise the entire nuclear power plant and its reactor system as well as fuel cycle facilities for the entire fuel cycle, from the front end to the back end.

This document discusses technology goals for Generation IV nuclear energy systems. Generation IV is a new generation of nuclear energy systems that can be made available to the world market by 2030, or earlier, and that offers significant advances toward meeting challenging goals. The goals are defined in the broad areas of sustainability, safety and reliability, economics, and proliferation resistance and physical protection. Sustainability goals focus on fuel utilization and waste management. Safety and reliability goals focus on safe and reliable operation and investment protection—essentially eliminating the need for emergency response. Economics goals focus on competitive life cycle and energy production costs and financial risk. Proliferation resistance and physical protection focus on safeguarding nuclear material and nuclear facilities.

Purpose of the Goals

The goals have three purposes. First, they define and guide the development and design of Generation IV systems. Second, they are challenging and will stimulate the search for innovative nuclear energy systems—both fuel cycles and reactor technologies. Third, they serve the basis for developing criteria to assess and compare the systems in a technology roadmap.

Generation IV Technology Roadmap

The Generation IV project was initiated by the United States in January 2000 and developed into a fully international effort. The Generation IV project is guided by a technology roadmap that identifies research and development (R&D) pathways for the most promising technologies. The roadmap gives attention to the technical and institutional barriers facing the technologies, as well as their research needs.

The roadmap primarily focuses on systems that can achieve deployment no later than 2030. The roadmap defines R&D objectives, activities, sequencing of tasks, cost estimates, and opportunities for national and international cooperation for selected nuclear energy systems.

Initially, a large number of innovative Generation IV systems were considered. After being evaluated, the most promising reactors and fuel cycles were chosen for further analysis of both their potential to meet the goals and the R&D needed to support their development and demonstration. These will be the subject of a Generation IV R&D program that advances the best concepts and provides a technical basis for their configuration. This will allow industry to select and eventually make one or more systems available to the market. Since past experience shows that significant programs may be needed to support development of a new system, it is expected that joint worldwide precompetitive development of Generation IV systems will offer the best path forward.

The public must have confidence in Generation IV systems. Key to public confidence is having a process that is open to public participation and designs that are transparent. The public must be involved in an interactive dialogue during the development process, especially in the early stages. The goals are a vital factor in building public confidence in Generation IV systems. Very importantly, Generation IV systems must be transparent, i.e., easily understood by the public and well supported by data, analysis, and demonstration. Their design information supports an understanding across a range spanning from the public at large to independent scientific experts. Successfully addressing public concerns also requires safe, secure, reliable, and economic performance of operating nuclear power plants and their future production of energy from Generation IV systems in accordance with sustainable development. For Generation IV systems, public participation divides into two periods. During the early part of the program, the public will be informed about the formulation of the roadmap and involved as the reactors and fuel cycle options are evaluated. During the latter part of the program, public participation will be sought by industry, which will select and bring a small number of nuclear energy systems to market.

Principles

The Generation IV technology goals derive from a set of guiding principles:

- Technology goals for Generation IV systems must be challenging and stimulate innovation
- Generation IV systems must be responsive to energy needs worldwide
- The Generation IV roadmap must define complete nuclear energy systems, not simply reactor technologies
- All candidates will be evaluated against the goals on the basis of their benefits, costs, risks, and uncertainties, with no technologies excluded at the outset.

Caveats

The Generation IV technology goals are intended to stretch the envelope of current technologies. Hence, the following caveats are important to note:

- The goals will guide the development of new nuclear energy systems. The objective of Generation IV systems is to meet as many goals as possible.
- The goals are not overly specific because the social, regulatory, economic, and technological conditions of 2030 and beyond are uncertain.
- The goals must not be construed as regulatory requirements.

GENERATION IV TECHNOLOGY GOALS

Eight goals for Generation IV nuclear energy systems are proposed in four areas: sustainability, safety and reliability, economics, and proliferation resistance and physical protection. The goals are arranged to facilitate the flow of information rather than to recommend an order of importance. Each goal is stated concisely. Supporting each goal is a discussion that clarifies the intent of the specific wording and the background from which it evolved. The discussion cites illustrative examples and suggests potential approaches. It is not meant to direct or constrain creativity and innovation. Also, much of the discussion is purposely drawn from worldwide experience that is useful in guiding the development of the goals.

Sustainability

Sustainability is the ability to meet the needs of present generations while enhancing the ability of future generations to meet society's needs indefinitely into the future. There is a growing desire in society for the production of energy in accordance with sustainable development. Since their energy is produced without combustion processes, existing and future nuclear power plants meet current and increasingly stringent requirements for clean air and avoid the emission of greenhouse gases. Sustainability requires conservation of resources, protection of the environment, preservation of the ability of future generations to meet their own needs, and avoidance of placing unjustified burdens on them. The two sustainability goals encompass the interrelated needs of effective fuel utilization and waste management.

Sustainability–1. Generation IV nuclear energy systems will provide sustainable energy generation that meets clean air objectives and promotes long-term availability of systems and effective fuel utilization for worldwide energy production.

Sustainability requires both the nuclear fuel to be available in the long term and the fuel cycle to be compatible with the environment. Conservation of resources encourages increasing fuel utilization beyond the level attained in current fuel cycles. Future nuclear energy systems have the unique opportunity to choose from a variety of fuels (e.g., uranium, thorium), reactor types (thermal, fast), and alternate fuel cycles (open, recycling). Evaluation of potential fuel cycles considered over their lifetimes could provide Generation IV systems a basis to optimize their long-term nuclear fuel usage and economics, while reducing the environmental impact of high-level radioactive waste and preserving resistance to proliferation. This strategy can increase the world energy supply significantly. These benefits need to be evaluated in terms of overall fuel cycle life cost, including disposition of high-level wastes and the need for infrastructure and technology. An additional factor to consider is the need to conserve other scarce materials or resources, which will ensure long-term availability of Generation IV systems.

Sustainability–2. Generation IV nuclear energy systems will minimize and manage their nuclear waste and notably reduce the long-term stewardship burden in the future, thereby improving protection of the public health and the environment.

All energy systems have a number of waste streams generated in energy production or by the eventual cleanup of the energy producing facilities. Nuclear energy wastes range from those resulting from the mining of raw materials to the wastes generated in nuclear reactors or by decommissioning and decontaminating (D&D) facilities. An important consideration of Generation IV systems is protection of public health and the environment by minimizing the amount and toxicity of discharged fuel and other high-level radioactive products, and by evaluating the fate and transport of their radionuclides. This consideration should take the additional need for infrastructure and advanced technology into account, working within the regulatory framework.

The United States and some other countries have adopted the once-through fuel cycle. Others use recycling to recover uranium and plutonium from the spent fuel to produce more power and reduce their needs for enrichment and new uranium. With recycling, the weapons-proliferation challenge increases, but the high-level radioactive residues with recycling are less toxic, occupy a much-reduced volume, and can be processed into a vitrified form before disposal. Reactors that operate with a high neutron energy can be used to regenerate the fissile material they consume, and at the same time transmute long-lived heavy elements to further improve the management of high-level waste and fuel utilization.

Disposition of discharged fuel or other high-level radioactive residues in a geological repository is the preferred choice of many countries involved in nuclear power generation, and good technical progress is being made. A number of countries are developing proposals in this area and will need to continue to implement policies that are both scientifically and technically sound and provide a basis for building public confidence, which remains crucial to the success of the geological repository strategy.

It is important that radioactive materials generated by Generation IV nuclear energy systems be produced in a form that best achieves safe and cost-effective waste management. Also, Generation IV systems should generate fewer low- and intermediate-level radioactive wastes and reduce their volume in order to decrease their impact at waste disposal sites.

Safety and Reliability

Safety and reliability are essential priorities in the development and operation of nuclear energy systems. During normal operation or anticipated transients, nuclear energy systems must preserve their safety margins, prevent accidents, and keep accidents from deteriorating into more severe accidents. At the same time, competitiveness requires a very high level of reliability and performance.

There has been a definite trend over the years to improve the safety and reliability of nuclear power plants, reduce the frequency and degree of off-site radioactive releases, and reduce the possibility of significant damage. Generation IV systems have goals to achieve the highest levels of safety and reliability and to better protect workers, public health, and the environment through further improvements. The three safety and reliability goals continue the past trend and are in accord with the regulatory policy to have designs that are safe and minimize the potential for severe accidents and their consequences.

Safety and Reliability–1. Generation IV nuclear energy systems operations will excel in safety and reliability.

This goal aims at increasing operational safety by reducing the number of events, equipment problems, and human performance issues that can initiate accidents or cause them to deteriorate into more severe accidents. It also aims at achieving increased nuclear energy systems reliability that will benefit their economics. Appropriate requirements and robust designs are needed to advance such operational objectives and to support the demonstration of safety that enhances public confidence.

During the last two decades, operating nuclear power plants have improved their safety levels significantly, as tracked by the World Association of Nuclear Power Operators. At the same time, design requirements have been developed to simplify their design, enhance their defense-in-depth in nuclear safety, and improve their constructability, operability, maintainability, and economics. Increased emphasis is being put on preventing abnormal events and on improving human performance by using advanced instrumentation and digital systems. Also, the demonstration of safety is being strengthened through prototype demonstration that is supported by validated analysis tools and testing, or by showing that the design relies on proven technology supported by ample analysis, testing, and research results. Radiation protection is being maintained over the total system lifetime by operating within applicable standards and regulations. The concept of keeping radiation exposure as low as reasonably achievable (ALARA) is being successfully employed to lower radiation exposure.

Generation IV nuclear energy systems must continue to promote the highest levels of safety and reliability by adopting established principles and best practices developed by the industry and regulators to enhance public confidence, and by employing future technological advances. The continued and judicious pursuit of excellence in safety and reliability is important to improving economics.

Safety and Reliability–2. Generation IV nuclear energy systems will have a very low likelihood and degree of reactor core damage.

This goal is vital to achieve investment protection for the owner/operators and to preserve the plant's ability to return to power. There has been a strong trend over the years to reduce the possibility of reactor core damage. Probabilistic risk assessment (PRA) identifies and helps prevent accident sequences that could result in core damage and off-site radiation releases and reduces the uncertainties associated with them. For example, the U.S. Advanced Light Water Reactor Utility Requirements Document requires the plant designer to demonstrate a core damage frequency of less than 10^{-5} per reactor year by PRA. This is a factor of about 10 lower in frequency by comparison to the previous generation of light water reactor energy systems. Additional means, such as passive features to provide cooling of the fuel and reducing the need for uninterrupted electrical power, have been valuable factors in establishing this trend. The evaluation of passive safety should be continued and passive safety features incorporated into Generation IV nuclear energy systems whenever appropriate.

Safety and Reliability–3. Generation IV nuclear energy systems will eliminate the need for offsite emergency response.

The intent of this goal is, through design and application of advanced technology, to eliminate the need for offsite emergency response. Although its demonstration may eventually prove to be unachievable, this goal is intended to stimulate innovation, leading to development of designs that could meet it. The strategy is to identify severe accidents that lead to offsite radioactive releases, and then to evaluate the effectiveness and impact on economics of design features that eliminate the need for offsite emergency response.

The need for offsite emergency response has been interpreted as a safety weakness by the public and especially by people living near nuclear facilities. Hence, for Generation IV systems a design effort focused on eliminating the need for offsite emergency response is warranted. This effort is in addition to actions that will be taken to reduce the likelihood and degree of core damage required by the previous goal.

Economics

Economic competitiveness is a requirement of the marketplace and is essential for Generation IV nuclear energy systems. In today's environment, nuclear power plants are primarily baseload units that were purchased and operated by regulated public and/or private utilities. A transition is taking place worldwide from regulated to deregulated energy markets, which will increase the number of independent power producers and merchant power plant owner/operators. Future nuclear energy systems should accommodate a range of plant ownership options and anticipate the increased use of distributed power. This means that there is a wider array of potential roles and options for deploying nuclear power plants, including load-following and smaller units.

It is anticipated that while Generation IV nuclear energy systems will primarily produce electricity, they may also find it profitable to produce a broader range of energy products beyond electricity. For example, potable water, process heat, or hydrogen will likely be needed to keep up with increasing worldwide demands and long-term changes in energy use.

Economics–1. Generation IV nuclear energy systems will have a clear life-cycle cost advantage over other energy sources.

A life cycle cost advantage is required to ensure active deployment of nuclear energy systems as a viable part of the world's energy supply. Life-cycle costs consist of four principal elements: (1) capital costs, (2) operation and maintenance costs, (3) fuel cycle costs, and (4) decommissioning and decontamination costs. Other factors are important, such as overall project duration, construction schedule, plant capacity factor, plant lifetime, and various financial assumptions for the project.

At present, capital cost and length of construction are the principal financial barriers to increased use of nuclear power, while operation and maintenance costs at existing plants have improved dramatically in recent years. For Generation IV projects, all elements of life-cycle costs should be addressed to produce an advantage over other energy sources, including current nuclear systems, and to ensure competitive energy production at time of deployment.

Economics–2. Generation IV nuclear energy systems will have a level of financial risk comparable to other energy projects.

In competitive capital markets, Generation IV nuclear energy projects must attract the capital required for their deployment. Accordingly, although the allowable level of financial risk is limited by the need to achieve the life-cycle cost advantage, Generation IV plants must independently demonstrate an acceptable level of financial risk to attract the necessary capital.

A number of factors are important: The cost and schedule risks associated with the construction, start-up, operation, and decommissioning must be well defined and managed for Generation IV projects. Choices must be made balancing the benefits of volume production and economy of scale. Achieving a comparable financial risk will also require that the systems adequately address external factors such as licensing and public concerns.

PROLIFERATION RESISTANCE AND PHYSICAL PROTECTION

Nuclear energy systems deployed for peaceful purposes were always expected to prevent nuclear weapons proliferation. The sustainability goal for Generation IV nuclear energy systems makes it all the more important to be highly resistant to proliferation through the diversion or undeclared production of nuclear materials at any point in the fuel cycle. This goal applies to all inventories of fissile materials in the facilities involved in mining, enrichment, conversion, fabrication, power production, recycling, and waste disposal.

Nuclear plants are highly secure and able to withstand severe external events such as earthquakes, floods, tornadoes, and fire. Their many protective features considerably reduce the impact of external or internal threats through the use of redundancy and separation of safety systems. This goal points to the need to address concerns from recent reviews of nuclear energy facility security and to provide secure physical protection against acts of terrorism.

Proliferation Resistance and Physical Protection–1. Generation IV nuclear energy systems will increase the assurance that they are a very unattractive and least desirable route for diversion or theft of weapons-usable materials and provide increased physical protection against acts of terrorism.

When nations acquired nuclear weapons in the past, they generally developed dedicated facilities to provide fissile materials for nuclear weapons rather than diverting such materials from civilian nuclear power systems. This does not mean that nuclear fuel cycles are, or can be, proliferation proof. Rather, the civilian nuclear fuel cycle has a history of being a less desirable route for production of weapons-usable materials. Generation IV nuclear energy systems should continue being highly resistant to proliferation and minimize the risk of proliferation by their operation.

The International Atomic Energy Agency (IAEA) has an essential and continuing role of preventing nuclear weapons proliferation through surveillance, monitoring, inspection, and accountancy of nuclear materials. The nuclear supplier states support the IAEA role by defining and enforcing export controls on proliferation-prone nuclear materials, technology, and equipment. All member states that are parties to the Non-Proliferation Treaty have pledged adherence to full-scope safeguards, i.e., compliance with these extrinsic (institutional) barriers to avoid proliferation.

Further, nuclear facilities have used technology to create intrinsic (design) barriers that enhance the extrinsic barriers and help prevent diversion of weapons-usable nuclear materials and misuse of nuclear facilities or technology for weapons purposes. An example of a key intrinsic barrier found in many civilian nuclear energy systems is that their nuclear materials become considerably less subject to diversion after irradiation because they are highly radioactive and their weapons-usable materials are unseparated.

Although very beneficial, intrinsic barriers are not sufficient by themselves. Rather, a combination of intrinsic barriers and extrinsic barriers is needed to achieve the required level of proliferation resistance and physical protection. To date, the combination of intrinsic and extrinsic features has made the diversion or theft of materials from the nuclear power fuel cycle very difficult and comparatively the least attractive to potential proliferators. Generation IV systems will extend this current regime into the innovative fuel cycles or reactor technologies and facilities that emerge as the most promising candidates. Means for easy detection and intrinsic barriers will be evaluated to avoid the misuse of novel features of Generation IV systems.

The means to increase physical protection should also adopt both intrinsic and extrinsic design features. Examples of intrinsic design features include reducing inventories and vulnerabilities of materials that could be the target of sabotage, increasing the protective structures and robustness of systems, and isolating or emplacing critical systems underground. Examples of extrinsic features include sophisticated systems for early detection and effective response to threats.